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Worldwide Soundscapes: A Synthesis of Passive Acoustic Monitoring Across Realms

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ABSTRACT

Aim: The urgency for remote, reliable and scalable biodiversity monitoring amidst mounting human pressures on ecosystems has sparked worldwide interest in Passive Acoustic Monitoring (PAM), which can track life underwater and on land. However, we lack a unified methodology to report this sampling effort and a comprehensive overview of PAM coverage to gauge its potential as a global research and monitoring tool. To address this gap, we created the Worldwide Soundscapes project, a collaborative network and growing database comprising metadata from 416 datasets across all realms (terrestrial, marine, freshwater and subterranean).

Location: Worldwide, 12,343 sites, all ecosystem types.

Time Period: 1991 to present.

Major Taxa Studied: All soniferous taxa.

Methods: We synthesise sampling coverage across spatial, temporal and ecological scales using metadata describing sampling locations, deployment schedules, focal taxa and audio recording parameters. We explore global trends in biological, anthropogenic and geophysical sounds based on 168 selected recordings from 12 ecosystems across all realms.

Results: Terrestrial sampling is spatially denser (46 sites per million square kilometre—Mkm^2) than aquatic sampling (0.3 and 1.8 sites/Mkm^2 in oceans and fresh water) with only two subterranean datasets. Although diel and lunar cycles are well sampled across realms, only marine datasets (55%) comprehensively sample all seasons. Across the 12 ecosystems selected for exploring

global acoustic trends, biological sounds showed contrasting diel patterns across ecosystems, declined with distance from the Equator, and were negatively correlated with anthropogenic sounds.
Main Conclusions: PAM can inform macroecological studies as well as global conservation and phenology syntheses, but representation can be improved by expanding terrestrial taxonomic scope, sampling coverage in the high seas and subterranean ecosystems, and spatio-temporal replication in freshwater habitats. Overall, this worldwide PAM network holds promise to support cross-realm biodiversity research and monitoring efforts.

1 | Introduction

Sounds permeate all realms on Earth—terrestrial, freshwater, marine and subterranean (Keith et al. 2022). Passive Acoustic Monitoring (PAM) captures soundscapes that document soniferous (i.e., sound-producing) organisms and human activities, and some geophysical events (i.e., biophony, anthropophony and geophony, respectively). In ecoacoustics and soundscape ecology (Pijanowski, Farina, et al. 2011; Sueur and Farina 2015), PAM can measure the impacts of global change (e.g., climatic shifts, urbanisation, deep-sea mining) (Kang et al. 2023; Sueur et al. 2019; Williams et al. 2022); monitor ecosystem health, recovery and restoration (Müller et al. 2023; Ross et al. 2024; Sethi et al. 2020); assess human–environment interactions (e.g., public health, cultural ecosystem services) (Alvarsson et al. 2010; Chen et al. 2022); and guide environmental management and conservation policies (e.g., protected areas, landscape planning) (Haver et al. 2019; Holgate et al. 2021).

Despite the wide-ranging and increasing soundscape sampling effort (Havlik et al. 2022; Sugai et al. 2019), global recording efforts across realms remain undescribed. Previous non-systematic qualitative reviews (Duarte et al. 2021; Lindseth and Lobel 2018) cannot describe data trends. Existing systematic reviews (Greenhalgh et al. 2020; Havlik et al. 2022; Scarpelli et al. 2020; Sugai et al. 2019) have not quantitatively addressed marine taxonomic coverage, terrestrial ecosystem coverage, nor spatio-temporal sampling distribution in fresh water, while the subterranean realm has yet to be reviewed. Notably, all reviews to date used only published data and involved only a small part of their respective communities. Indeed, practitioners of PAM are currently only networked within realms (e.g., terrestrial/marine), and often use distinct methods. Marine scientist networks using PAM exist (Boyd et al. 2015), but the freshwater community is nascent, and the terrestrial community is often fragmented by taxa. Methodological differences are also striking: acoustic calibration and sound propagation modelling are advanced in aquatic studies (Wang et al. 2014) but seldom considered in terrestrial ones (but see Haupert et al. (2022) and Sousa-Lima et al. (2013)); artificial intelligence can increasingly identify species on land (Nieto-Mora et al. 2023), whereas most aquatic sounds are still challenging to identify (Looby, Erbe et al. 2023; Parsons et al. 2023).

Overall, a global PAM network could increase knowledge transfer, resulting in more efficient and consistent methods, analyses and cross-system syntheses (Sugai et al. 2019). Cross-realm PAM studies can advance theoretical (Ross et al. 2023) and applied solutions. For instance, organisms' sound durations follow a common distribution across multiple realms (de Sousa et al. 2022). Also, soundscapes can track terrestrial and marine resilience and recovery to disturbance (Gottesman et al. 2021). Transnational sampling could form the basis for comprehensive soniferous biodiversity monitoring, just as community-initiated telemetry databases (Kays, Davidson, et al. 2022) and collaborative camera trap surveys (Kays, Cove, et al. 2022) have advanced entire research fields. A global PAM network could complement existing biodiversity-monitoring networks, establish historical biodiversity baselines, support systematic long-term and large-scale monitoring and connect with the public through citizen science. Such information is critical to inform global biodiversity policies (Moersberger et al. 2024) such as the Kunming-Montreal Global Biodiversity Framework.

We present the 'Worldwide Soundscapes' project, the first global PAM meta-database and network (https://ecosound-web.de/ecosound_web/collection/index/106). We use it to quantify the known state of PAM efforts, highlight apparent sampling gaps and biases, illustrate the potential of cross-realm PAM syntheses for research and federate PAM users. The project currently comprises 357 contributors who collated metadata from 416 passively recorded, stationary, replicated soundscape datasets. Metadata describe the exact spatio-temporal coverage, sampled ecosystems (*sensu* International Union for Conservation of Nature Global Ecosystem Typology: IUCN GET), transmission medium (air, water, or soil), focal taxa (IUCN Red list), audio recording settings, as well as data and publication availability. We inferred coverage within administrative (Global ADMinistrative Database: GADM; International Hydrographic Organisation: IHO) and protected areas (World Database on Protected Areas: WDPA) from geographic locations. We selected recordings referenced in the meta-database to quantify soundscape components (biophony, anthropophony, and geophony) across 12 ecosystems from all realms. We showcase how the soundscape components can be used to answer exemplary macroecology, conservation biology and phenology research questions and we identify opportunities to advance the global PAM network. The publicly accessible meta-database (Darras et al. 2024) continues to grow to enhance accessibility of data and remains open for metadata contributions, facilitating exchange among researchers and future syntheses.

2 | Methods

2.1 | Database Construction

The Worldwide Soundscapes database began in August 2021 using collaborative, peer-driven metadata collation (Darras et al. 2024). It represents the current state of knowledge of PAM within our network. We additionally conducted focal publication searches to plug coverage gaps by inviting the respective corresponding authors. We posted the call for contributors on specialised ecoacoustics platforms and social media, and kept the project open for any contributor owning suitable soundscape recordings. We communicated by emails in English, Spanish, French, Portuguese, German, Russian, and Chinese to federate users in our network. Of 581 contacted contributors potentially involved in PAM, 61% provided metadata. We included metadata from larger, national or international groups such as the Silent Cities project (Challéat et al. 2024), Ocean Networks Canada (Heesemann et al. 2014), and the Australian Acoustic Observatory (Roe et al. 2021). Primary contributors provided the metadata and bear the responsibility for their accuracy. Research assistants checked the coherence of the metadata input (beyond automated data format checks) and primary contributors cross-validated metadata displayed as maps and graphical timelines. The database information page and content are integrated as a project in our online collaborative ecoacoustics platform ecoSound-web (Darras et al. 2023) that also hosts the annotated soundscape recordings of the case study (https://ecosound-web.de/ecosound_web/collection/show/49).

Soundscape recording datasets needed to meet four criteria: (1) stationary—mobile recorders have variable spatial assignments, thus we excluded recordings from cars, transect walks or towed deployments; (2) passive—obtained from unattended recorders; (3) ambient—omni-directional, non-triggered recordings, under non-experimental conditions; (4) spatially or temporally replicated (Figure 1)—to disentangle spatial and temporal effects from other soundscape determinants. Datasets were defined as spatially replicated when several sites were sampled simultaneously, and temporally replicated when a site was sampled over multiple days at the same time of day. Sampling sites and days were our elemental units for defining replication; however, in other contexts, spatial replicates may, for instance, be required to be in the same habitat, and temporal replicates may be defined across multiple full moon nights. Taken together, our requirements homogenise the dataset to enable general, unified statistical analyses across datasets.

2.2 | Time and Space

Soundscapes result from geophysical phenomena as well as wildlife and human activities that are broadly determined by solar and lunar cycles and geographical positions on the planet relative to the poles or equator or the land and water surface. We defined and calculated spatial coverage as the number of audio sampling sites ('sites' hereafter) and spatial density as the number of sites relative to each realm's areal extent. Spatial sampling extent could have been defined as the area bounded by sites, but calculating extents on the world sphere is conceptually challenging for large extents. Spatial coverage calculation is further hindered by the fact that the sampling area covered at each site is generally unknown: they are rarely measured in terrestrial sites but sometimes simulated in marine environments (Erbe and Thomas 2022). Detection spaces vary with sound source intensity, frequency, directivity, recording medium temperature, currents, pressure, atmospheric humidity (for air), habitat structure and ambient sound level (Darras et al. 2016; van Parijs et al. 2009). Underwater, at depths above the wavelength, detection spaces are greater due to the higher density of the recording medium. Our measure of spatial sampling density using points per area is thus provisional. Temporal extent was defined as the time range from the start of the first to the end of the last recording of a site, temporal coverage as the time sampled for that site and temporal density as the proportion of time sampled within the temporal extent.

We quantified latitudinal and topographical distribution by collecting coordinates, elevation and depth data for each site. Topography values on land were either provided by the contributors or filled in automatically using the General Bathymetric Chart of the Oceans surface elevation data (GEBCO 2025). For freshwater sites, depth values below the water surface were provided by the contributors, and for subterranean sites, depth below the land surface was recorded. We assigned sampling sites to administrative areas (GADM divisions for freshwater and land, IHO for sea areas) and extracted their WDPA category. Sites' climates were geographically classified into tropical (between −23.5° and 23.5° latitude), polar (below −66.5° or above 66.5° latitude) and temperate (between polar and tropical regions).

Primary contributors coded their exact recording times for each site using deployment start and end dates and times and operation modes (or combinations thereof). Operation modes included continuous operation, which lasted from the deployment start to its end; scheduled operations that had daily start and end times; and periodical operations that used duty cycles. A temporal framework was devised to quantify sampling coverage in three solar and lunar cycles using the timing of sound recordings relative to specific events (Figure 3). Seasonal coverage was inferred only for temperate sites by splitting the year into four meteorological seasons (winter: December–February, spring: March–May, summer: June–August, fall: September–November, reversed for Southern latitude sites). The daily cycle was split into four diel windows delimiting dawn (from astronomical dawn start at −18° solar altitude until 18° solar altitude), day, dusk (from 18° solar altitude to astronomical dusk end at −18° solar altitude) and night. The lunar illumination cycle was split into two time windows centred on the full and new moon phases. Thus, extrema and ecotones in the temporal cycles define time windows, and in temperate zones, equinoxes roughly correspond to thermal ecotones. Seasonal cycles in tropical and polar regions arising from precipitation patterns were not considered in this analysis, but future frameworks should consider recent developments (Littleboy et al. 2024).

2.3 | Ecological Characterisation

We assigned sites to ecosystem types following the IUCN GET (https://global-ecosystems.org). Sites were assigned hierarchically to realms, biomes and functional groups. 'Core' realms are terrestrial, marine, freshwater, and subterranean, while 'transitional' realms represent the interface between these. For example, the transitional marine–freshwater–terrestrial realm comprises the brackish tidal biome, which contains coastal river deltas as a functional group. We calculated major occurrence areas of all functional groups based on ecosystem maps (Keith, Ferrer-Paris, Nicholson, Bishop, et al. 2020) to quantify spatio-temporal extent, coverage, and sampling density within realms and biomes. For the spatial and temporal result sections, sites were assigned to their 'parent' realm (i.e., the first mentioned realm in the compound transitional realm names). The results

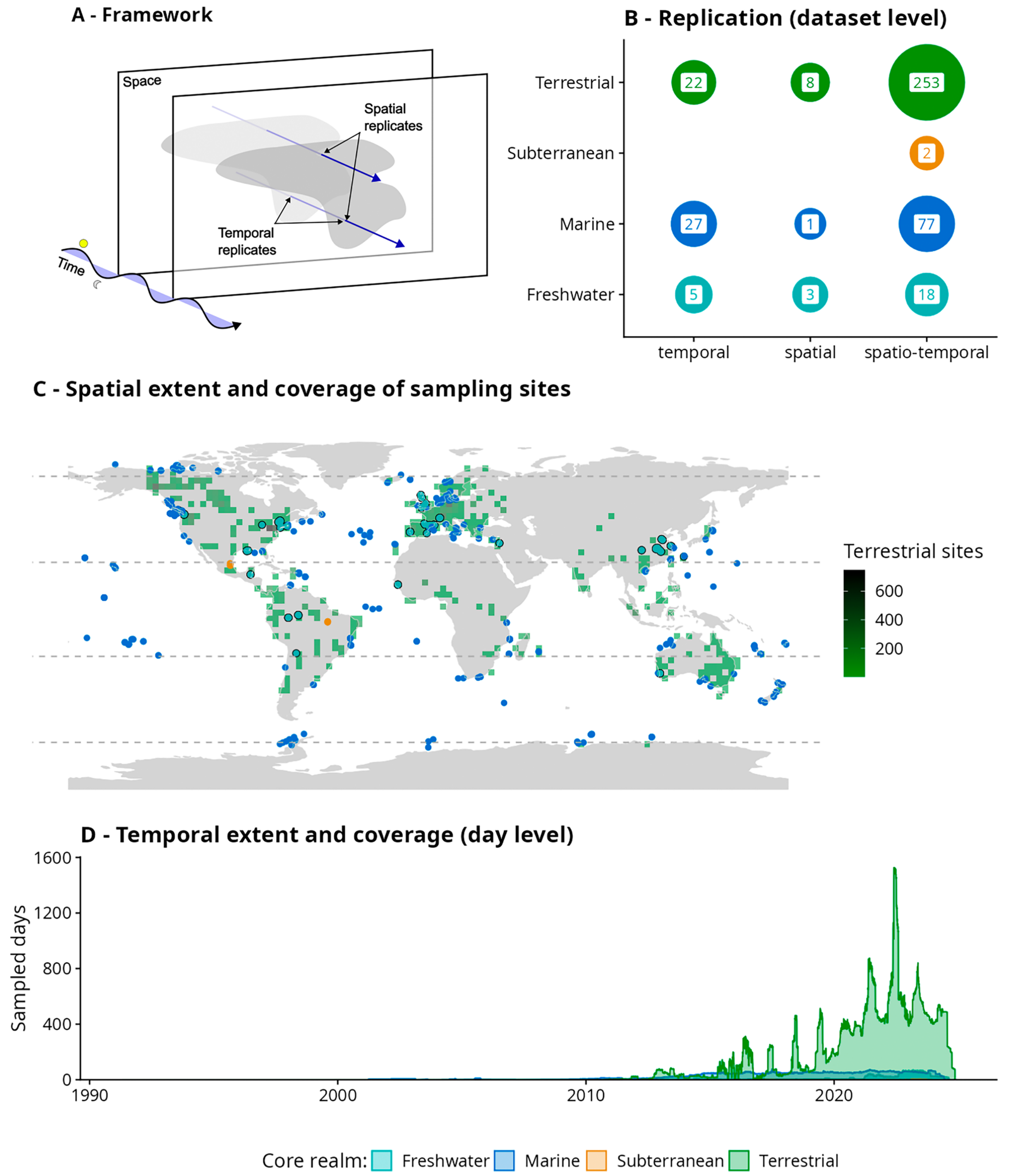

FIGURE 1 | Overview of Worldwide Soundscapes meta-database. (A) Framework used to define spatial and temporal replicates. (B) Number of datasets in each core realm for the different replication levels. (C) Spatial extent and coverage, based on sampling sites, split by core realm. Due to their higher representation and to avoid overlapping site clusters, terrestrial site densities were plotted on a 3° resolution raster (Interactive map: https://ecosound-web.de/ecosound_web/collection/index/106). (D) Temporal extent and coverage, based on recorded days, split by core realm. An enlarged version of panel D without terrestrial sites can be found in Figure S3. For panels B–D, sites from transitional realms were assigned to their parent core realm.

section 'Sampling in ecosystems' separates results among core and transitional realms. Deployments were linked to IUCN Red List taxa (class, order, family or genus) when studies were designed for monitoring these taxa; other deployments could be collected without taxonomic focus.

2.4 | Acoustic Frequency Ranges

We needed to determine the spectral scope of soundscape recordings. Microphones (including hydrophones and geophones) have variable frequency responses, usually declining with frequencies above the human-audible range. Additionally, digital recorders restrict the spectral range of the recording with the sampling frequency. Contributors provided audio parameters for their deployments: sampling frequency, high-pass filters, microphone and recorder models. More recent metadata contributions include the number of channels, audio amplification and bit depth.

2.5 | Soundscape Case Studies

To illustrate how the database can be used for macroecology, conservation biology and phenology analyses, we selected 168 recordings across a variety of topographical, latitudinal and anthropisation conditions—all fundamental gradients of assembly filters in both terrestrial and marine realms (Keith et al. 2022)—belonging to 12 IUCN GET functional groups (i.e., ecosystem types): large lowland rivers, small permanent freshwater lakes, riverine estuaries, bathypelagic ocean waters, island slopes, photic coral reefs, tropical montane rainforests, tropical lowland rainforests, plantations, urban ecosystems, polar outcrops and aerobic caves. We aimed for four spatial replicates within the same functional group, with 10-min audible sound recordings (at least 44.1 kHz sampling frequency) starting at sunrise, solar noon, sunset, and solar midnight from the same date during the biologically active season. However, the available data sometimes yielded fewer replicates or a lower sampling frequency in one case (Table S3). We acknowledge that this targeted, non-systematic selection of recordings is not statistically representative of global patterns but rather illustrative of the database's potential for future studies.

In each soundscape recording, we identified the three fundamental soundscape components: biophony, anthropophony, and geophony. For example, biophony could comprise acoustic cues (vocalisations or sonant displays) from non-human vertebrates or invertebrates; anthropophony comprises human speech or noises from any human technologies (e.g., engines, explosions; sometimes termed 'technophony'); geophony comprises geophysical sounds (e.g., from wind, rain or waves). Soundscape recordings were uploaded to ecoSound-web (Darras et al. 2023) for annotation (https://ecosound-web.de/ecosound_web/collection/show/49): KD listened to them while visually inspecting spectrograms (Fast Fourier Transform window size of 1024) at a density of 1116 pixels per 10 min. Visible and audible sounds were annotated using rectangular boxes on the spectrogram, with defined coordinates in the time and frequency dimensions, bounding the corresponding sound closely. Annotations were classified into different soundscape components and could overlap if they were simultaneously visible or audible. Soundscape components above 22.05 kHz and sounds caused by microphone or recorder self-noise were excluded from the analysis. All annotations were validated by the recordists using the peer-review mode on ecoSound-web, which allowed them to view and listen to the same recording to accept, revise or reject annotations, and to check whether annotations were missing. Revised or rejected annotations were corrected by KD before a second validation. Finally, acoustic space occupancy for each soundscape component in each recording was calculated as the proportion of the sampled spectro-temporal space (Luypaert et al. 2022) (i.e., annotations area divided by total area of spectrogram; range: 0–1), and silence was the proportion of the acoustic space not covered by any soundscape component. We used the total coverage of annotations of the same soundscape component, excluding overlaps, to compute acoustic space occupancy. For instance, a windy episode covering half of the spectrogram's duration from 1 to 3000 Hz would cover ~7% of the acoustic space (300 s $\times$ 3000 Hz/600 s $\times$ 22,050 Hz).

We asked whether biophony occupancy increases with proximity to the equator, whether biophony is negatively correlated with anthropophony and whether phenology patterns differ across functional groups. Statistical models predicting biophony occupancy were Bayesian beta regression models (four chains of 4000 sampling iterations with 2000-warmup iterations, thinning rate of 1) fitted with the R package brms (Bürkner 2017). Models converged as determined by trace plots and R hat values smaller than 1.1. The number of data points equaled the number of recordings ($N = 168$). The models using latitude and anthropophony were mixed-effect models including the functional group as a random intercept. The phenology model used diel time windows, coded as a numeric variable with integers from 1 to 4, and functional group, as well as their interaction, as predictors. This allowed for the comparison of effects of the functional group on the phenology profile, approximated by a linear regression, by measuring statistically significant differences in the slopes of that regression depending on the functional group.

3 | Results

3.1 | Summary Dataset Statistics

To date, 416 validated soundscape meta-datasets (hereafter 'datasets') have been registered in our database from across the globe, dating back to 1991 (Figure 1D). A dataset comprises the metadata of a study or project. Based on the IUCN GET definition of four core realms, our database includes 283 terrestrial, 105 marine, 26 freshwater and 2 subterranean validated datasets. The transmission medium was air for terrestrial datasets (except for soil in one dataset), mostly water for aquatic datasets (eight above-water datasets, mostly fresh water). In the subterranean realm, one dataset used aerial recordings, while the other used underwater recordings. The majority of datasets (84%) included both spatial and temporal replicates (Figure 1B). Few datasets have openly accessible recordings (8%–12% excluding subterranean realm, Figure S1). Presently, few terrestrial and freshwater datasets (28% and 19%, respectively) are associated with DOI-referenced publications in contrast to marine datasets (50%), excluding the subterranean realm with too few

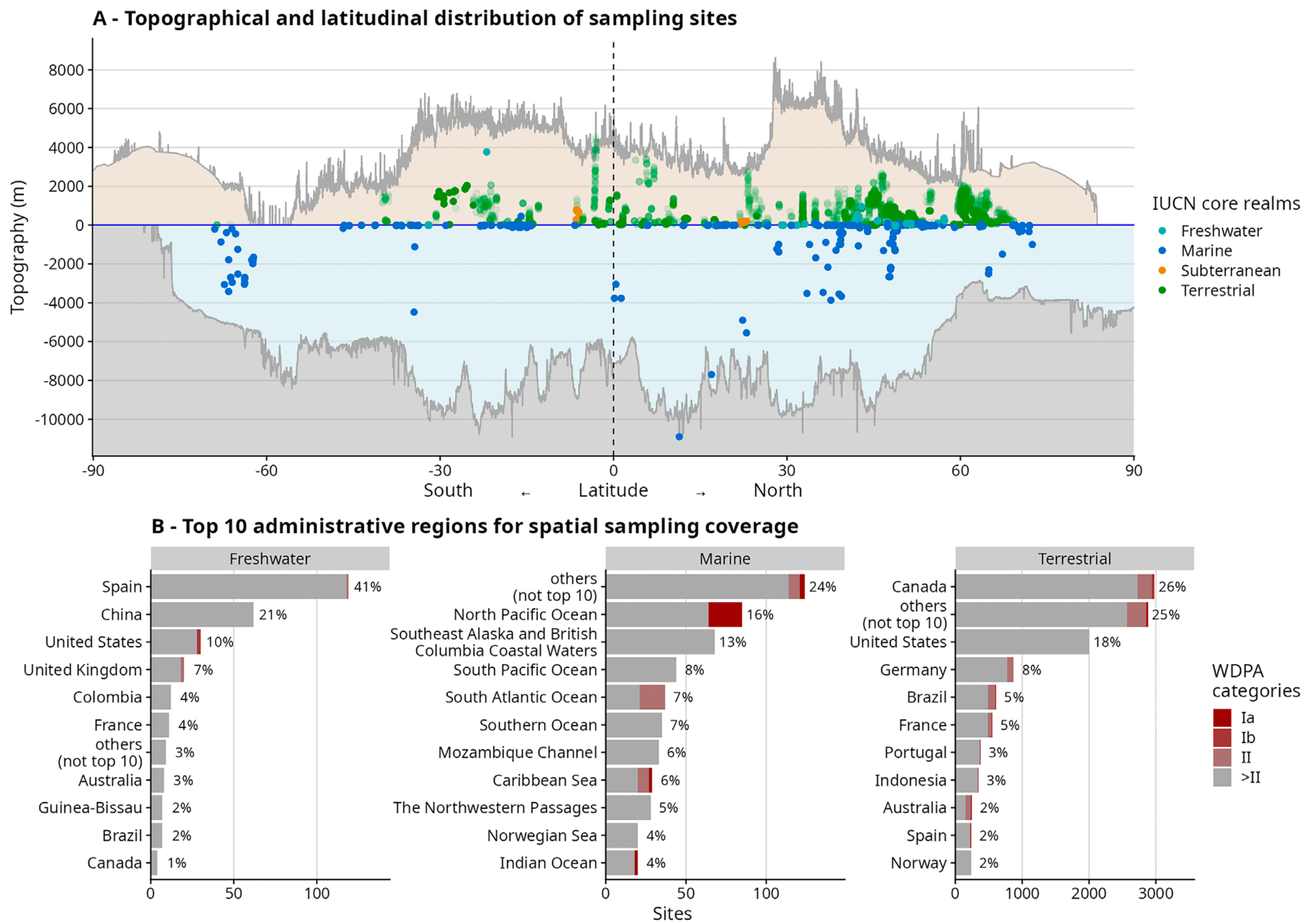

FIGURE 2 | Spatial distribution of sampling sites. (A) Latitudinal and topographic distribution of sampling sites across core realms. Due to their higher representation and to avoid overlapping site clusters, terrestrial sites are shown with transparency. The minimum (deepest seafloor) and maximum (highest elevation of land or sea level) topographical limits (dark grey lines) are shown against latitude, based on General Bathymetric Chart of the Oceans data (GEBCO 2025). Minimum topography above sea level and maximum topography below sea level were set to zero as the sea level represents the minimum and maximum in these cases. (B) Number of sampling sites within different administrative regions (GADM level 0 and IHO sea areas), split by core realm, across WDPA categories (Ia: Strict nature reserve; Ib: Wilderness area, II: National park). The areas that do not belong to the top 10 in terms of datasets have been aggregated under 'others'. The 13 subterranean sites are not shown. Sites from transitional realms were assigned to their parent core realm.

datasets (Figure S1). The decline in coverage in 2023 and onwards (Figure 1D) presumably reflects that ongoing or recent studies have not yet been reported. Overall, the recordings registered in our database would use a minimum of 5904 TB of storage space, assuming 50% losslessly compressed, single-channel recordings at the most common and lowest bit depth of 16.

3.2 | Spatial Sampling Coverage and Density

The database contains 12,343 sampling sites, including 147 polar, 9214 temperate and 2982 tropical sites (Figure 1C). On land, 11,368 sites are located within 86 (out of 263) GADM level 0 areas (i.e., countries, Figure 2B), primarily in the Northern Hemisphere (Table S1). Most terrestrial sites occur in Canada (26%), followed by the United States (18%), but a significant proportion are elsewhere in the world (25% do not belong to the top 10 GADM areas). Few terrestrial sites (8%) are located in WDPA category Ia, Ib or II areas, corresponding to the highest protection levels. Our database currently lacks data from vast areas in Russia, Greenland, Antarctica, North Africa and Central Asia. Site elevations range from sea level up to 4548 m (Figure 2A), but mountains above 4000 m in the Northern Hemisphere and above 2000 m in the Southern Hemisphere (except for Kilimanjaro), as well as the Transantarctic Mountains, are currently not represented in the database. At sea, 637 sites are located within 35 (out of 101) IHO sea areas. Administratively, most marine sites are widespread among IHO areas (24% do not belong to the top 10 IHO areas), but the North Pacific Ocean as well as the Southeast Alaskan and British Columbia Coastal Waters contain a large proportion of marine sites (16% and 13%, respectively). Many sites are situated in WDPA high-protection category Ia and II areas (12%). Our database currently lacks datasets from Arctic waters off Eurasia and Southeast Asian coastal areas. Sampling sites span ocean depths from sea water surface to depths of 10,090 m, but tropical bathypelagic and Southern benthic areas are poorly represented (Table S2). Few GADM areas (11) are represented in the 324 freshwater sites. Spain holds most freshwater sites (41%), followed by China (21%). Few freshwater sites (2%) are in WDPA category II or Ib areas. Freshwater bodies are

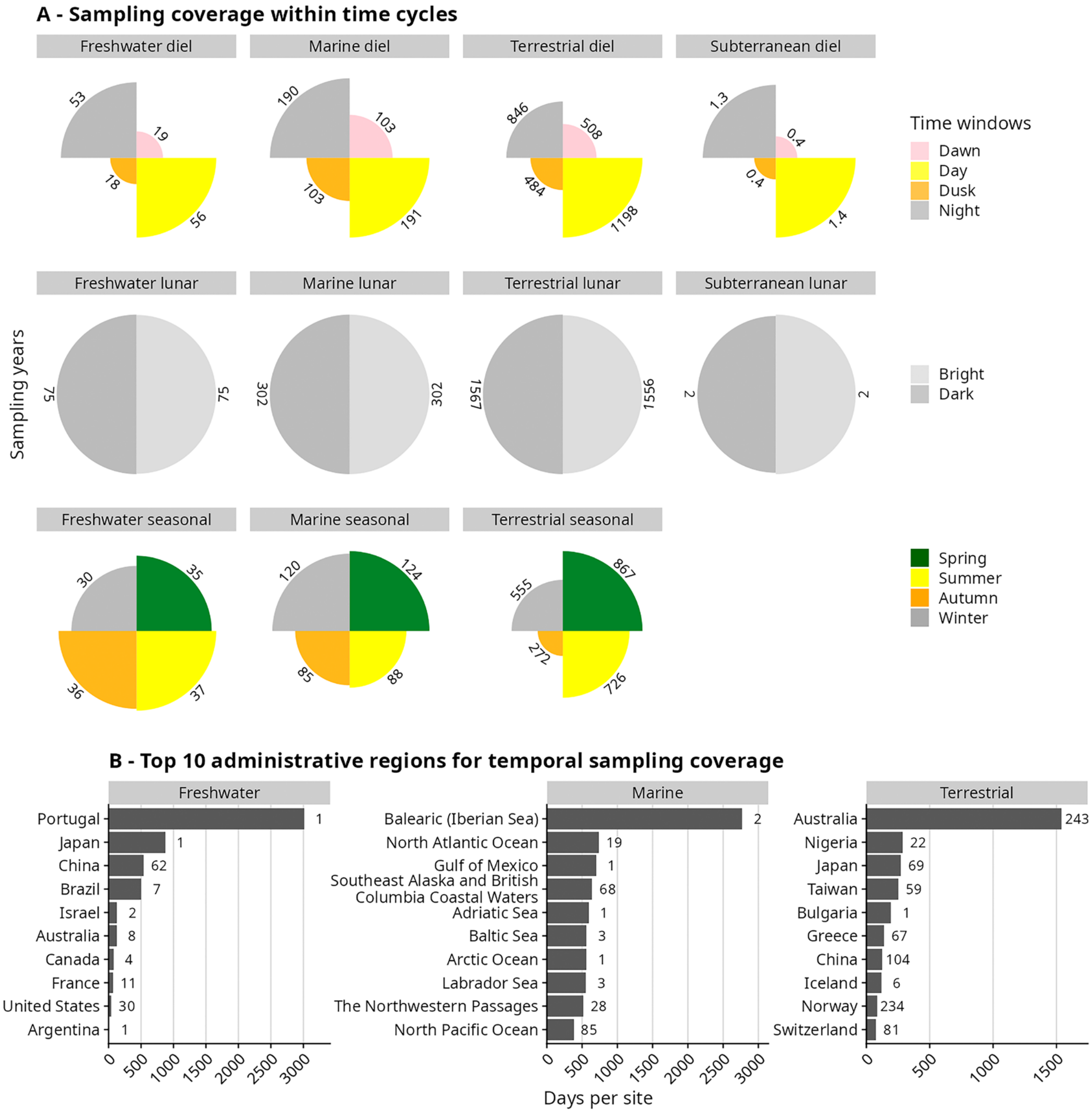

FIGURE 3 | Temporal sampling distribution. (A) Temporal sampling coverage across solar and lunar cycles for all core realms. Cycles consist of solar (daily and seasonal) and lunar time cycles (lunar phase), divided in time windows. Seasons were only analysed in temperate regions and subterranean sites were all in tropical regions. Sampling coverage is represented with sampling years in number labels. (B) Mean number of sampling days per site within administrative regions (GADM level 0, IHO areas, WDPA categories), split by core realm. The 13 subterranean sites are not shown. Numbers to the right of bars indicate the number of sites the means were calculated from. Sites from transitional realms were assigned to their parent core realm.

sampled at elevations up to 3770 m and were sampled up to 25 m depth. Mountain freshwater bodies and those in Africa, Asia, and Oceania are currently poorly represented in our database (only one site at 3770 m). The database contains 14 subterranean sites situated in Brazil and Mexico between 34 and 810 m elevation and a depth of up to 20 m.

3.3 | Temporal Sampling Extent, Coverage and Density

We compare sampling coverage (in years sampled by recordings, summed over sites) across time windows of the diel cycle, the lunar phases and the seasons (Figure 3A). Dawn and dusk diel windows are shorter than day and night diel windows for most locations and correspondingly less intensively sampled. The lunar phase cycle is evenly covered across realms and comprehensively covered within datasets (Figure S2). In the terrestrial realm, daytime coverage surpasses night-time coverage (1198 vs. 846 years), while 76% of datasets sampled all diel time windows. Terrestrial temperate datasets mostly sampled spring (867 years, 36%) and summer (726 years, 30%) while 22% sampled all seasons. In conjunction with the higher sampling intensity in the northern temperate zones, this causes the observed peaks in Figure 1D. Terrestrial temporal coverage per site is highest in Australia (1541 days - Australian Acoustic Observatory). In the marine realm, diel coverage is even, as 87% of marine datasets sampled all diel time windows. Marine temperate datasets have high and similar coverage for winter and spring (120 and 124 years, combined 59% of seasonal coverage) and 55% cover the full seasonal cycle. Marine temporal coverage per site is highest in the Balearic (2771 days). In the freshwater realm, temporal coverage among diel time windows is even, and 81% of freshwater temperate datasets sampled all diel time windows. By contrast, 36% of datasets sampled all seasons. Freshwater temporal coverage per site is highest in Portugal (3009 days). The subterranean tropical sites primarily covered the day- and night-time.

3.4 | Sampling in Ecosystems

Our database includes 82 of the 107 functional groups (as per IUCN GET version 2.1.1 for spatial data). All biomes are covered except anthropogenic shorelines, the subterranean tidal biome, anthropogenic subterranean voids, and anthropogenic subterranean freshwaters (Table S2). The terrestrial realm has the third-largest extent and the highest spatial sampling density among realms (45.8 sites per million square kilometres (Mkm^2) over entire temporal extent), but temporal coverage is comparatively low (30% sampled out of 203 days of mean extent per site). The most commonly sampled terrestrial biome is the temperate-boreal forests and woodlands biome (56% of sites). The marine realm is the most extensive, but spatial sampling density is the lowest (0.3 sites per Mkm^2), while temporal sampling coverage is the highest among all realms (66% out of 377 days sampled). The most commonly sampled marine biomes are the marine shelf and pelagic ocean waters (55% and 35% of sites respectively). The freshwater realm has low spatial sampling densities (1.8 sites per Mkm^2) and high temporal sampling densities (68% out of 238 days sampled). Lakes are the most commonly sampled freshwater biome (48% of sites). The terrestrial–freshwater realm, representing 81% of the area of transitional realms, has the third-highest spatial sampling density (7.9 sites per Mkm^2) and moderate temporal sampling density (18% out of 2363 days sampled). The marine–freshwater–terrestrial realm (including 26 sites in coastal river deltas, saltmarshes and intertidal forests) has the second largest temporal extent (465 days per site). The subterranean realm, when excluding endolithic systems, is the smallest core realm and it includes seven tropical sites (all in tropical aerobic caves) sampled with a low temporal coverage (1% out of 129 days sampled). The subterranean–freshwater realm includes five sites in underground streams and pools, sampled with a low temporal coverage over the largest temporal extent (6% out of 1109 days sampled).

3.5 | Target Taxa and Frequency Ranges

Most marine datasets do not target specific taxa (66%) and record wide frequency ranges from 0.009 to 31 kHz (mean bounds of frequency ranges across datasets, Figure 4B). Marine datasets that focus on single taxa comprise fish (12%, 0.002–20 kHz) and cetaceans (6%, 0.006–7 kHz). Similarly, most freshwater datasets are taxonomically unspecific (56%) and cover frequencies from 1 to 29 kHz. Some datasets (14%) focus on ray-finned fish, covering frequencies from 0.001 to 23 kHz. By contrast, terrestrial datasets mostly target single taxa and record narrow frequency ranges. Bird-focused datasets are most common (44%), spanning frequencies from 0.056 to 21 kHz, while bat-focused datasets are next (12%) and range from 5 to 139 kHz. Taxonomically unspecific datasets account for 24% of terrestrial datasets, covering a broad range from 0.2 to 23 kHz. Generally, datasets targeting multiple taxa use wider frequency ranges than those targeting single taxa.

3.6 | Soundscape Case Studies

The selected soundscape recordings spanned latitudes from 69° South to 67° North (Table S3 and Figure 5A). Biophony dominated, with an average soundscape occupancy of 27% across all ecosystems. Notable examples include the photic coral reefs in Okinawa, Japan, with snapping shrimps and grunting fish choruses, and the tropical lowland rainforests in Jambi, Indonesia, with buzzing insects and echoing bird and primate songs, showing soundscape occupancy of 75% and 61%, respectively (Lin et al. 2023). Only marine island slopes (off Sanriku, Japan) and polar outcrops (Antarctica) contained minimal biophony (0% and 2%, respectively). Geophony was absent in most of our soundscape samples, with the exception of high wind noise in polar outcrops (14%) and some wind in montane tropical forests and urban ecosystems (both 5%). On average, anthropophony occupied 9% of the soundscapes. Cities (Jambi, Indonesia; Montreal, Canada) exhibited the highest anthropophony (43%) with prevalent engine noise and human voices, while deep-sea mining and vessel communication signals caused high anthropophony in marine island slopes (32%) (Chen et al. 2021). Silence was most prevalent in bathypelagic ocean waters (96%) and polar outcrops (82%).

The selected soundscapes revealed greater biological activity closer to the equator, a negative relationship between biophony and anthropophony, and variable phenology patterns of soniferous organisms over the diel cycle (Figure 5). We detected a negative correlation of biophony occupancy with increasing distance from the equator ($p_{\text{negative}} = 1$) and with anthropophony occupancy ($p_{\text{negative}} = 0.98$). The phenology model predicted a negative slope for the effect of the diel time windows in tropical montane forests, different from the positive slope in bathypelagic ocean waters ($p_{\text{different}} = 1$), and a negative slope in small permanent freshwater lakes, likely different from the one in bathypelagic ocean waters ($p_{\text{different}} = 0.94$). More complex relationships than linear regressions can be expected, which might lead to further detectable differences between functional groups, so this simple analysis on our limited dataset constitutes a minimal proof that the phenological profiles differ among functional groups. We displayed loess smooths for the biophony occupancy values for each diel time window and realm (Figure 5B), revealing their widely differing phenology patterns.

4 | Discussion

The 'Worldwide Soundscapes' project has—to our knowledge—assembled the first global meta-database of PAM datasets across realms. We analysed its current content to quantify sampling extent, coverage and density across spatiotemporal and ecological scales. We analysed soundscapes from 12 ecosystems to investigate macroecological, conservation biology and phenological trends. The database remains open for contributions, can be openly accessed to source datasets and helps initiate collaborative studies (Darras et al. 2024). Next, we discuss the state

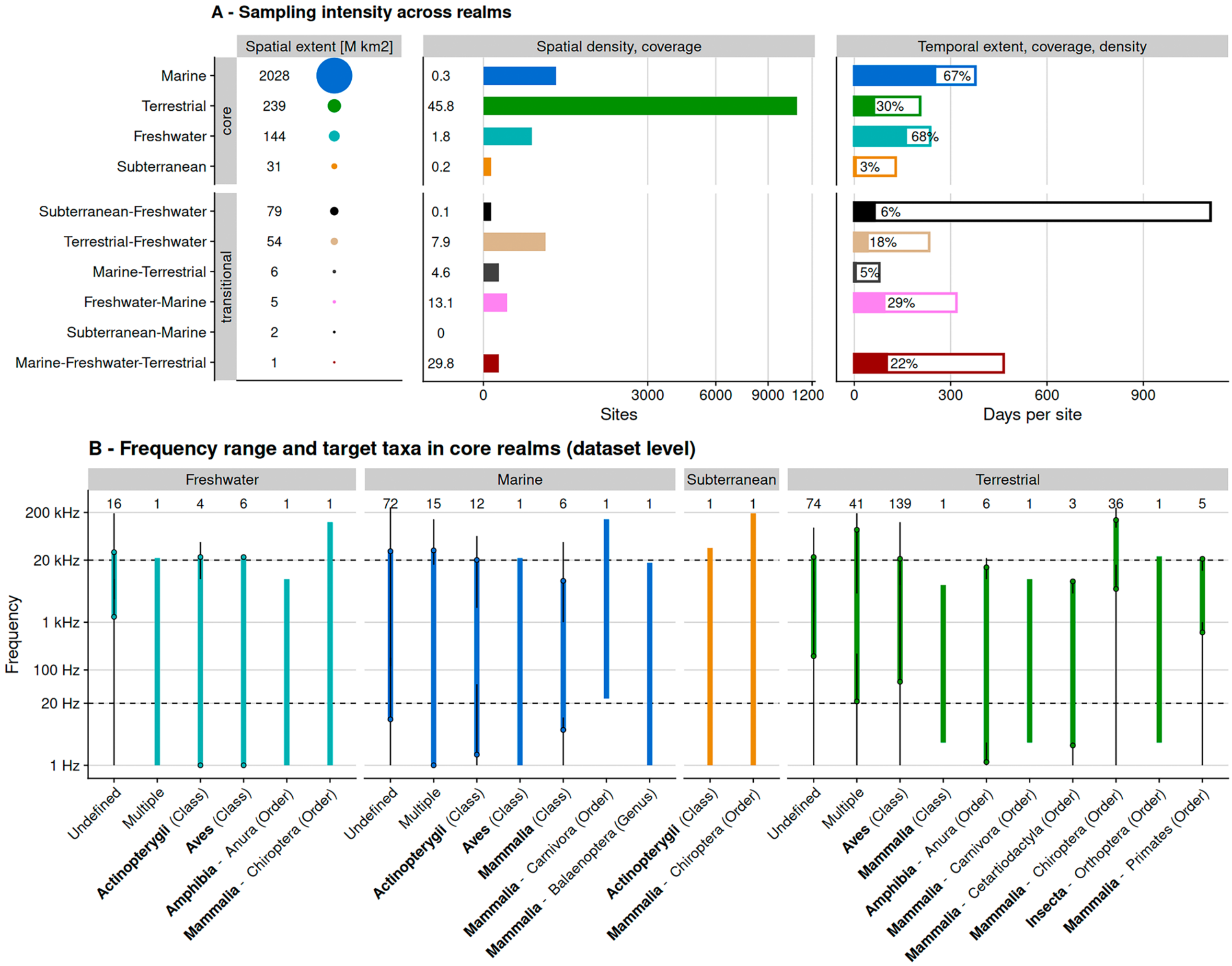

FIGURE 4 | Sampling distribution across ecological scales. (A) Sampling intensity, split between core and transitional realms: Spatial extent of realms, based on major occurrence areas according to IUCN GET (coloured disk area proportional to area); spatial sampling density (in sites per Mkm^2) and coverage (in number of sites); temporal extent (mean range between first and last recording day), coverage (days sampled per site) and density (proportion of days sampled per extent). (B) Frequency ranges of datasets across realms (using Nyquist frequency i.e., actual recorded frequencies) for the main studied taxa. The dots at the ends of coloured lines represent means of the lowest and highest recorded frequencies, and the ranges between the minimum and maximum of these values are indicated with black error bars. The limits of human hearing are indicated with dashed lines. Number of datasets indicated above lines—datasets can be counted several times if they contain deployments targeting different taxa. Data from transitional realms were assigned to their parent core realm in panel B.

and potential of PAM globally (Table 1). While we aim for large-scale research questions here, the database can also be used to address more specific questions, for instance using the finely resolved taxonomic information that we recorded, or for within-realm syntheses.

Our results likely represent global PAM trends, even though they may be biased by the project contributors' background. Our terrestrial spatial coverage is similar to an existing systematic review (Sugai et al. 2019). Our database gaps in North Africa and Northeastern Europe correspond with the paucity of bioacoustic datasets for these regions in the Xeno-Canto bioacoustic repository (Xeno-canto Foundation 2012). Our database comprises 637 marine sampling locations, while a recent systematic review compiled 991 (Havlik et al. 2022) from published data. Although the latter review's locations are represented at the dataset level (which can comprise several sites), most overlap with our finer site-level locations (Figure S4). Marine tropical waters that are under-represented in our database reflect gaps found in the International Quiet Ocean Experiment network coverage (IQOE n.d.). Our marine and terrestrial database's spatial coverage is thus broadly comparable with published data, but it is more detailed as the exact sampling locations are known. Our database's temporal coverage is also more finely resolved with exact sampling times, and thus not directly comparable with previous work. To our knowledge, no other spatially explicit review of freshwater sampling or synthesis of subterranean PAM coverage exists for comparison. Finally, as our database originates from an active network of researchers, it represents the current availability of mostly as-yet-unpublished data (Figure S1).

Geographic coverage differs strikingly among realms: marine coverage is sparse but widespread; terrestrial coverage is comparatively intensive in the Americas, Australia and Western Europe; freshwater coverage is scattered. This partly reflects the gap between high-income countries, which have the resources

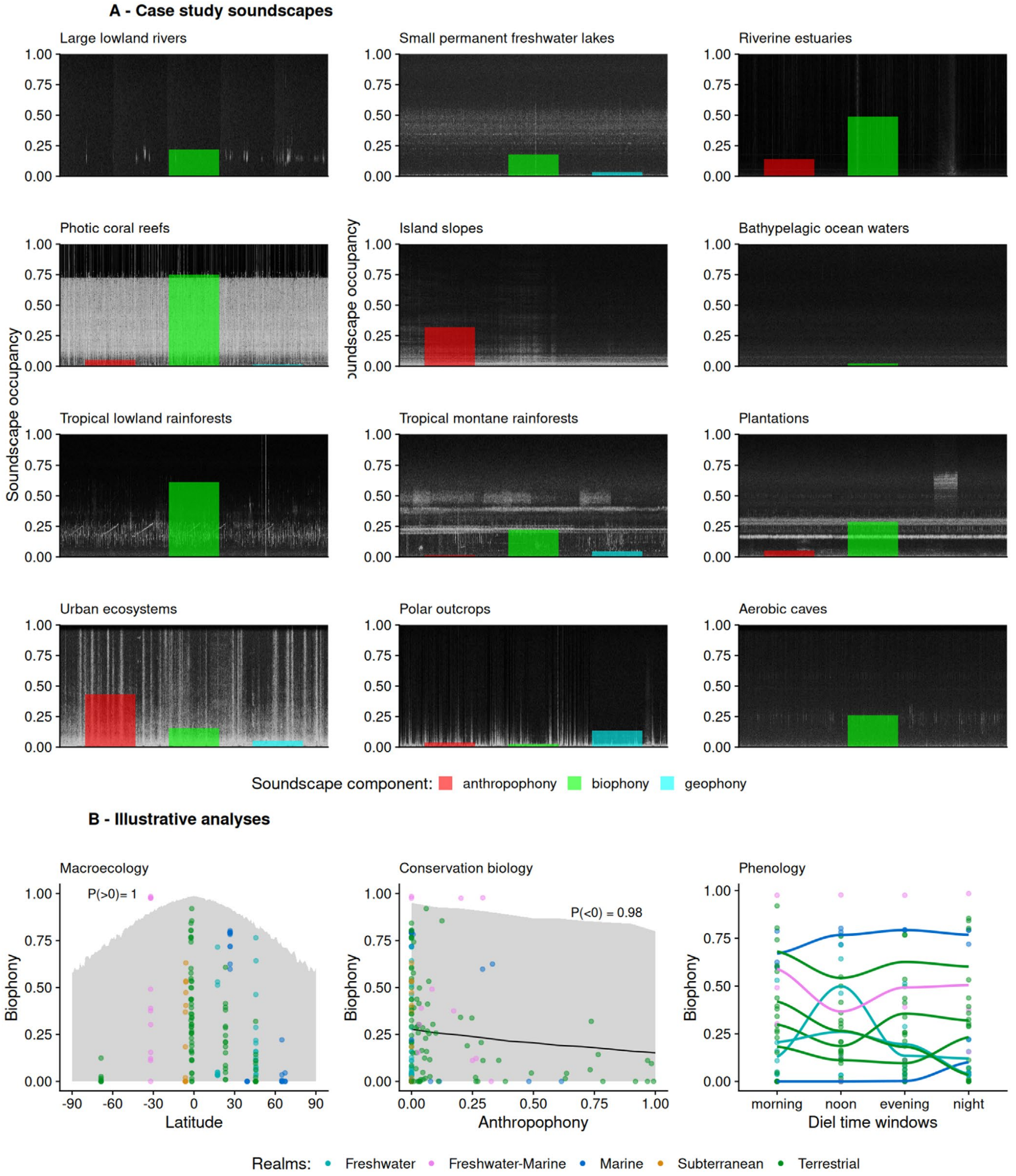

FIGURE 5 | Soundscape components analysis. (A) Mean acoustic space occupancy of soundscape components (biophony, geophony, anthropophony) shown with bar plots, as calculated from spectrogram annotations for 12 selected ecosystems, measured in proportion of spectro-temporal space used, over 168 recordings covering the time windows of the diel cycle. Annotated recordings are accessible at https://ecosound-web.de/ecosound_web/collection/show/49. Sample spectrograms are shown in the background. (B) Soundscape component occupancy data illustrate three research questions linked to macroecological patterns (i.e., biophony with distance from equator relationship), conservation biology trade-offs (i.e., biophony with anthropophony relationship); and phenological trends (i.e., biophony loess smooths along diel time windows for each functional group). Grey ribbons indicate 95% credible intervals and numbers indicate probabilities of positive or negative relationships.

TABLE 1 | An agenda towards a global PAM coverage and network.

Aims	Opportunities
Increasing spatial and ecosystemic coverage	• Affordable shallow underwater recorders • Autonomous setups for extreme environments on land • Explore subterranean realm, dynamic freshwater bodies • Deploy at high latitude and elevation on land
Increasing temporal and taxonomic coverage	• Longer deployments with duty cycles on land • Cover all seasons in freshwater and on land • Scale up to inter-annual cycles • Higher sampling frequencies • Disabling high-pass filters and triggers
Increasing collaboration	• Work interdisciplinarily with speleologists, urban ecologists, soil and deep-sea benthic scientists • Foster international missions to work at large scales • Collaborate, invest, and fund work with under-represented countries • Disseminate results in multiple languages
Interoperability	• Calibrate equipment and measure detection ranges • Build accessible and sustainable data repositories • Design and adopt standards for deployment, reporting, and analysis • Integrate PAM into biodiversity and remote sensing databases

to carry out conservation and active ecosystem management actions, and developing countries, which are home to the majority of biodiversity hotspots (and are some of the most densely populated areas). Accessibility and technical limits in extreme environments also drive geographic patterns: high latitudes and elevations entail low temperatures that present challenges for operation and maintenance, some of which can be solved with robust power setups (solar panels, freeze-resistant batteries). Marine deployments are generally even more constrained due to costly and demanding underwater work, but some deployments reach the polar regions as water temperatures are buffered below the freezing point. Affordable underwater recorders (Lamont et al. 2022) may help to intensify sampling of marine coastal areas and close gaps in freshwater coverage. By contrast, terrestrial monitoring is relatively straightforward. Northern temperate areas outside of Northeastern Europe are comparatively better covered, while the tropics outside of Africa are better represented. Gaps in North Africa, Central Asia and Northeastern Europe may arise from unequal research means and differing priorities between countries. Addressing these gaps will help correct spatial biases (Beck et al. 2014) and identify high-priority, unique research areas that should be included in global assessments.

Currently, only marine studies achieve relatively even coverage of temporal cycles. Indeed, offshore deployments—especially in the deep sea—are expensive and limited-duration deployments are not cost-effective (Rountree, Aguzzi et al. 2020). Marine soundscapes fluctuate stochastically (Siddagangaiah et al. 2022), but the ocean buffers water temperatures so that animals are active year-round. Although lunar phases affect marine life (Hernández-León et al. 2001; Mougeot and Bretagnolle 2000; Simonis et al. 2017) and shape tidal ecosystems, we did not consider lunar tides. In the terrestrial and freshwater realms, most deployments cover the entire diel cycle, but monitoring on land often focuses either on diurnal birds or on nocturnal bats (Sugai et al. 2019). By contrast, although seasons also drive acoustic activity cycles on land (Grinfeder et al. 2022; Krause et al. 2011), spring- and summertime monitoring is disproportionately common, and we lack a complete understanding of seasonal dynamics (Figures 1D and S3). Terrestrial deployments, in particular, may be short for logistical reasons: in the cold, batteries drain faster or fail and road access is harder; in arid regions, fire hazards complicate long-term deployments; in general, recorders are at risk of theft, and limited equipment may be cycled between sites (Sugai et al. 2020). Lunar phases also influence land animals (Kronfeld-Schor et al. 2013) and should be explicitly considered in future study designs. Overall, we encourage longer duration setups with regularly spread sampling inside temporal cycles to alleviate the higher expenses for energy and storage, as well as trade-offs with spatial coverage (Van Wilgenburg et al. 2024). Global changes impact soundscapes in largely unpredictable ways through changing species distributions and phenology, necessitating higher and unbiased coverage across multiple time scales—including inter-annual ones—to successfully monitor ongoing changes (Desjonquères et al. 2022).

Re-use of soundscape datasets is restricted by their taxonomic focus. Many soundscape recordings sample particular frequencies, often in the human-audible range (Luypaert et al. 2022), although biophony ranges from infrasound to ultrasound. For instance, studies of toothed whales or bats often use triggers and high-pass filters to cope with high data storage demands by recording purely ultrasonic recordings only when signals are detected, resulting in spectrally restricted and temporally biased soundscape recordings. Less studied taxa, such as anurans and insects, could effectively be co-sampled by adjusting ongoing terrestrial deployments. We encourage terrestrial researchers to maximise frequency ranges (and to broaden diel coverage—see above) to enhance interdisciplinary collaboration. In oceans, taxonomically untargeted, long, and regular deployments, coupled to large detection ranges, concurrently sample many taxa

(Lillis and Boebel 2018). Mutual sampling campaigns can share resources to mitigate potentially prohibitive equipment, power, storage, transportation and post-processing costs (Sousa-Lima et al. 2013). Emerging embedded-AI audio detectors may offer an alternative to continuous and broadband recording (Höchst et al. 2022), but whole soundscape recordings will remain essential for broader application.

In every realm, ecosystems await acoustic discovery. Except for two datasets from aerobic caves and underground streams, we currently lack data from subterranean realms (e.g., anthropogenic voids, sea caves), while endolithic systems may be the only ecosystem for which PAM is probably irrelevant. Access is usually challenging or restricted for non-specialists, but subterranean biodiversity shows high spatial turnover (Zagmajster et al. 2018). Freshwater data were less rare, but several datasets with unreplicated sampling could not be included. Temporary, dynamic water bodies (seasonal, episodic, and ephemeral ecosystems), although prevalent (Messager et al. 2021), are not yet well studied (Table S2), though most are accessible from land. Notably, aquatic realms feature important peculiarities: extraneous sounds from the air can be captured in so-called holo-soundscapes in freshwater and shallow coastal areas (Rountree, Juanes et al. 2020), and particle motion (that accompanies sound) impacts aquatic organisms (Popper and Hawkins 2018). Advances in soundscape research are imminent as the freshwater acoustic research community is growing rapidly (Linke et al. 2018). In the oceans, sound propagates comparatively far and multiple biomes can be sampled at once (e.g., recorders on the seafloor sample pelagic waters too) so that all ecosystems (i.e., functional groups) are covered by at least one site. On land, sampling is biased towards biodiverse forests, while rocky habitats (young rocky pavements, lava flows and screes) and some vegetated temperate ecosystems (cool temperate heathlands, temperate subhumid grasslands) appear poorly sampled. Within the IUCN GET framework, soil soundscapes also belong to the terrestrial realm, and to date only one spatio-temporally replicated dataset is in our database, despite recent efforts to record soil soundscapes (Maeder et al. 2022; Metcalf et al. 2024). Soil and benthic habitats may also be sampled with geophones to record infrasonic vibrations used to sense the environment (e.g., by insects, frogs, elephants, interstitial fauna and benthic fish) (Šturm et al. 2022).

Our database highlights well-known global sampling biases (Hughes et al. 2021) which could be resolved with collaboration and communication to remove cultural and socioeconomic barriers (Amano et al. 2016). Technological progress for more affordable equipment renders PAM more accessible in lower income countries (Hill et al. 2019; Lamont et al. 2022). However, high- and deep-sea work remains considerably more expensive, and tropical developing countries in particular often lack funding for marine programmes requiring large vessels, underwater vehicles or cabled stations on the seafloor (Rountree, Aguzzi et al. 2020). Our network currently consists of active members from 58 countries. Collaborative projects, such as data compilations, shared sea missions and equipment loans, should promote the establishment of soundscape research communities (Reboredo Segovia et al. 2020). However, equitable, collaborative efforts will also require capacity-building so that local researchers can independently process, analyse, and interpret PAM-derived data. Increased international collaboration with scientists and local stakeholders supporting citizen science (Newson et al. 2015) in heavily underrepresented regions would improve not only data coverage but also representation and dialogue within the field.

Collaborative soundscape research relies on interoperable data. We harmonised metadata with a bottom-up approach leading to our global inventory. Comprehensive standards for PAM equipment, deployment, reporting and data analysis are needed for enabling comparative, global analyses. However, such standards do not currently exist, even though initiatives for the marine realm are ongoing (Roch et al. 2016; Wall et al. 2021). Few affordable solutions exist for sharing large audio data volumes (Darras et al. 2023), underlining the need for distributed soundscape recording repositories (Sugai and Llusia 2019). Marine oil and gas industry projects routinely upload data as part of their efforts to mitigate noise impacts on marine animals (Southall et al. 2008), but these recordings often focus on frequencies relevant to seismic prospecting and access may be restricted (Haver et al. 2018). Furthermore, recording equipment requires calibration (Jarrett et al. 2024), sound detection spaces need to be measured (Darras et al. 2016; Haupert et al. 2022), and data privacy must be ensured on land (Cretois et al. 2022). In parallel, species sound libraries (Görföl et al. 2022; Looby, Vela et al. 2023; Parsons et al. 2022; Xeno-canto Foundation 2012) grow and continue to provide invaluable acoustic and taxonomic references, without which automated soundscape analyses for soniferous organisms would not be possible. International organisations such as the Global Biodiversity Information Facility (GBIF) will be key to roll out standards (e.g., Darwin Core) in a top-down manner. For the moment, we encourage early planning for archiving data. In the future, the Worldwide Soundscapes will interoperate with other databases to close remaining coverage gaps and enhance standardisation.

A unified approach to macroecology with PAM is now possible. More comprehensive coverage is needed to decisively answer research, conservation and management questions that PAM can address, so we encourage prospective contributors to curate their metadata and join our inclusive project. The project co-leads assist prospective members, and the project website (https://ecosound-web.de/ecosound_web/collection/index/106) provides information about metadata requirements. While metadata were previously added to the database after vetting by project managers, new features enable contributors to manage their meta-datasets (i.e., collections, sites, meta-recordings) directly online. A large portion of the PAM community is willing to collaborate across realms and form global networks. We advocate for a bolder PAM effort to inform the agenda of soundscape ecology (Pijanowski, Villanueva-Rivera, et al. 2011), reaching out to places where no sound has been recorded before. The research community may open new avenues to study environmental effects on acoustic activity (Desjonquères et al. 2022), social species interactions (Briefer et al. 2024), human-wildlife relationships (Lin et al. 2023), function and phylogeny (Gasc et al. 2013), soundscape effects on human health (Buxton et al. 2021), acoustic adaptation and niche hypotheses (Ey and Fischer 2009; Hart et al. 2021), macroecological patterns across ecosystems (Keith et al. 2022) and initiate an integrated approach to noise impacts on wildlife.

PAM is an established method that can be applied over large spatial and temporal scales. However, consistent, large-scale monitoring of the Earth's soundscapes is direly needed and essential to establish baselines for historical trends (Pilotto et al. 2020) and quantify rapid changes in biodiversity and natural systems. Funding schemes should encourage the use of PAM in large-scale biodiversity monitoring projects and require the submission of expert-vetted soniferous animal detections to platforms such as GBIF (GBIF: The Global Biodiversity Information Facility 2024). The initiation of PAM projects linked to the GEO BON (Gonzalez et al. 2023; Towards a Transnational Acoustic Biodiversity Monitoring Network (TABMON) n.d.) should further expand the use and acceptance of PAM. Integrated PAM workflows similar to the 'BON in a box' framework, which already include some marine acoustic projects, would help to generate distribution maps and to infer Essential Biodiversity Variables for soniferous wildlife, which could underpin the evaluation of progress towards threat reduction and ecosystem service provision of the Kunming-Montreal Global Biodiversity Framework (Batist and Campos-Cerqueira 2023). Soundscapes are just beginning to be recognised in legislation as an ecosystem feature to be preserved (Leiper 2020). By building collaborations around the knowledge frontiers identified here, we can aim to comprehensively describe and understand the acoustic make-up of the planet.

Author Note

The present study has involved people who carried out PAM-based studies as primary contributors. Their willingness to be informed through a mailing list, responsibility for their metadata, approval for sharing the meta-data publicly and willingness to participate in this study as co-authors were explicitly stated in an online form-based collaboration agreement. Primary contributors who became co-authors all fulfilled either data curation (e.g., as providers of structured metadata) or project administration (e.g., as principal investigators designing the corresponding study) roles and additionally a manuscript revision role. They could be corresponding authors for published studies, referred contacts for unpublished studies or principal investigators, and were asked to identify further primary and secondary contributors of their study. Primary contributors could become co-authors, and secondary contributors are acknowledged here. Some primary contributors were invited as co-leads to expand the network for particular realms or biomes and are listed in the first-tier authors list. Primary contributors who provided soundscape recordings in addition to metadata are also listed in the first-tier authors list. All primary contributors were asked to identify further contacts to reach a comprehensive coverage for the database.

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Consent

Necessary permits from landowners or environmental protection agencies, precautions to limit biological contaminations (e.g., biofilm on marine recorders), approvals for animal welfare and local ethics committee reviews were the responsibilities of the respective primary contributors.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The metadata used for all analyses except the case studies are archived in Zenodo: https://zenodo.org/records/14216871. We provide the R script for reproducing the metadata analysis and graphs, as well as the R script and data for reproducing the case study analysis and graph. The demonstration collection providing all case study recordings is hosted here: https://ecosound-web.de/ecosound_web/collection/show/49.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.